

Beyond standard model Higgs physics: prospects for the High Luminosity LHC

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This article summarises a talk given at Higgs Hunting 2014 on projections of the sensitivity of the ATLAS and CMS experiments to beyond standard model Higgs physics at the High Luminosity Large Hadron Collider. We describe results on vector boson scattering, searches for additional neutral Higgs bosons in two Higgs doublet models and flavour changing neutral current top decays.

I. INTRODUCTION

The High Luminosity Large Hadron Collider (HL-LHC) is a major upgrade of the LHC to deliver an integrated luminosity of 3000 fb^{-1} within a decade to both ATLAS and CMS. One of its main goals is permitting the precise measurement of the properties of the recently discovered standard model (SM) Higgs like boson [1, 2].

In this report, we highlight a few recent results related to probing the nature of this boson and sensitivity to beyond standard model Higgs physics. Section II discusses the expected sensitivity to non-standard model Higgs couplings in weak boson scattering processes. The following section III describes the current estimates for sensitivity to searches for additional neutral Higgs bosons in two Higgs doublet models. Finally, section IV reviews the projections for flavour changing neutral current top decays involving Higgs bosons and section V concludes and discusses the next steps.

II. WEAK BOSON SCATTERING

In addition to providing a mechanism for electroweak symmetry breaking, the standard model Higgs boson also restores the unitarity of scattering of weak bosons such as $W^+W^- \rightarrow W^+W^-$. Figure 1 shows examples of Feynman diagrams involving vector boson scattering in proton proton collisions. The first diagram has only vector bosons in the core interaction while the second diagram (interfering negatively with diagrams of the first type) involves a Higgs boson. The third diagram illustrates how anomalous quartic vector boson couplings can contribute to the same final state. Due to the strong interference of the first and second diagrams, any beyond the standard model processes like the third diagram are expected to significantly modify the kinematic distributions of the final state particles.

Comparing the middle and right diagrams it becomes also apparent that contributions from new heavy bosons would first be seen as anomalous *quartic* rather than triple gauge couplings because such bosons contribute to quartic couplings at leading order while the contribution to triple gauge couplings only affects higher orders [3].

The experimental signature is two jets with a large difference in pseudorapidity, multiple leptons and in some cases missing transverse energy:

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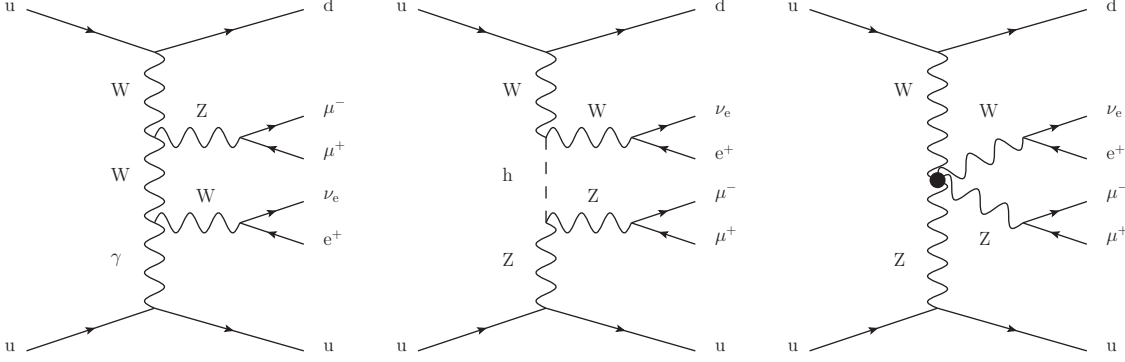


FIG. 1. Example diagrams related to vector boson scattering at the LHC for a given final state. The left diagram is a vector boson scattering process, the middle diagram shows a process involving the standard model Higgs boson and the right diagram corresponds to anomalous quartic gauge couplings.

- $pp \rightarrow ZZjj \rightarrow \ell^+ \ell^- \ell^+ \ell^- jj$

This channel suffers from a small branching ratio, but has a very characteristic final state with four charged leptons on the other hand. The kinematics of the outgoing diboson system is fully reconstructable, making it possible to measure the cross section as function of centre of mass energy of the diboson interaction. The ATLAS selection [4] requires four charged leptons (electrons or muons) with a transverse momentum above 25 GeV which must be consistent with two Z boson candidates (pairs of opposite charge and same flavour). At least two jets with a transverse momentum above 50 GeV are required and two of them must form a dijet mass above 1 TeV.

- $pp \rightarrow W^\pm Zjj \rightarrow \ell^\pm \nu \ell^+ \ell^- jj$

Cross section times branching ratio is larger in this final state than in the ZZjj channel, but reconstructing the full kinematics of the diboson system becomes more difficult due to the presence of a neutrino.

Both ATLAS [4] and CMS [5] have estimated up to which energy scale anomalous couplings could be observed at HL-LHC. The ATLAS (CMS) event selection requires exactly three high transverse momentum leptons (electrons or muons) with $p_T > 25$ (20) GeV. Two of them must be consistent a Z boson decay (same flavour and opposite charge, invariant mass close to the Z boson mass). At least two jets with a transverse momentum above 50 GeV must be present with a dijet invariant mass of at least 1000 (600) GeV. The CMS analysis additionally requires that the two jets are separated by at least 4.0 in pseudorapidity.

The ATLAS study makes the assumption that the missing transverse energy is entirely due to the neutrino and requires that the invariant mass of the neutrino and the charged lepton not associated to the Z boson decay is equal to the W boson mass in order to estimate the longitudinal component of the neutrino momentum.

Expected distributions of the WZ (transverse) mass, which are used to discriminate anomalous quartic coupling signals from standard model processes, are shown in Figure 2.

- $pp \rightarrow W^+ W^+ jj \rightarrow \ell^+ \nu \ell^+ \bar{\nu} jj$

Replacing also the second Z boson by a W boson, cross section times branching ratio increases again with respect to the previous final states, but the second neutrino makes the reconstruction of the full kinematics of the weak boson scattering system impossible.

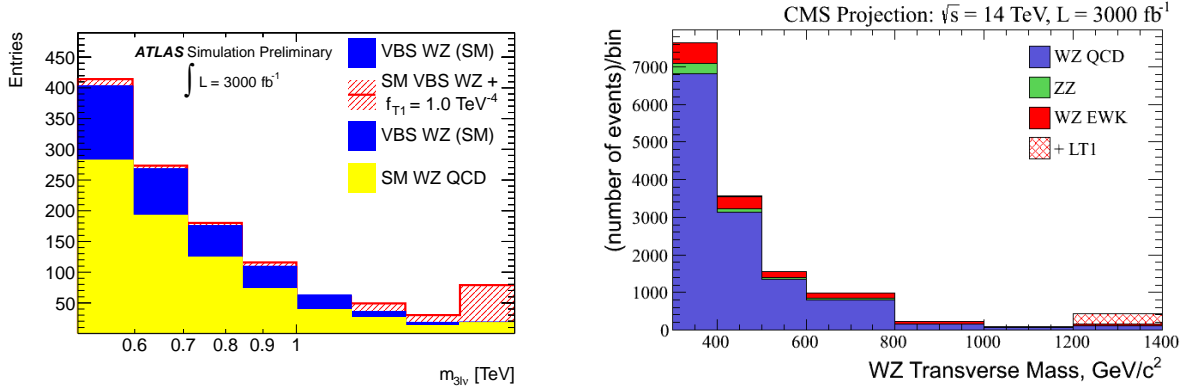


FIG. 2. WZ invariant mass distributions in the $pp \rightarrow WZjj \rightarrow \ell^\pm \nu \ell^+ \ell^- jj$ channel for the ATLAS study [4] (left) and WZ transverse mass distribution for CMS [5] (right).

The ATLAS experiment has studied the sensitivity at HL-LHC for this channel. Exactly two identified leptons of the *same* charge, with a transverse momentum above 25 GeV are required in the selection together with at least two identified jets with a transverse momentum above 50 GeV. The invariant mass of the two selected highest p_T jets must exceed 1 TeV. The distribution of the mass of the two jets and two leptons is used to discriminate signal from background.

Both ATLAS and CMS experiments have sensitivity to this channel already with LHC Run I data [6, 7].

Table I summarises the expected sensitivities for these three final states.

experiment	final state	operator	dimension	5σ reach for 3000 fb^{-1}
ATLAS	$\ell^+ \ell^- \ell^+ \ell^- jj$	$\mathcal{O}_{\Phi W}/\Lambda^2$	6	16 TeV^{-2}
ATLAS / CMS	$\ell^\pm \nu \ell^+ \ell^- jj$	$\mathcal{L}_{T,1}/\Lambda^4$	8	$0.55 / 0.6 \text{ TeV}^{-4}$
ATLAS	$\ell^\pm \nu \ell^\pm \nu jj$	$\mathcal{L}_{S,0}/\Lambda^4$	8	4.5 TeV^{-4}

TABLE I. Projected 5σ discovery reach for the vector boson scattering analyses at HL-LHC. For the same strength of the coupling and order of the operator, smaller numbers correspond to a higher scale Λ up to which deviations from the standard model can be seen at 5σ significance. The dimension 6 and 8 operators are defined in [8] and [9]. For comparison, limits on the S_0 operator coefficient obtained with Run I data are $^{+40}_{-38} (^{+43}_{-42}) \text{ TeV}^{-4}$ [7].

III. TWO HIGGS DOUBLET MODELS

Two Higgs Doublet models (2HDM) are an extension of the standard model where a second Higgs doublet is added, giving rise to three neutral Higgs bosons h, H and A and two charged Higgs bosons H^\pm . The most widely known example of a 2HDM is the minimal supersymmetric standard model (MSSM). 2HDMs can be parametrised in several ways, a common set of parameters [10] is the following: the four masses of the Higgs bosons m_h, m_H, m_A and m_{H^\pm} , the ratio of the vacuum expectation values of the two doublets $\tan\beta, \sin(\beta - \alpha)$ (where α is the mixing angle between the CP-even Higgs bosons) and the Higgs potential parameters m_{12}^2, λ_6 and λ_7 .

Both ATLAS [11] and CMS [12] experiments have estimated their sensitivity to searches for the heavy CP-even Higgs boson H and the CP-odd Higgs boson A at HL-LHC.

A. $pp \rightarrow H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$

The selection in this channel is very similar to the four lepton selection in the search for the standard model Higgs. ATLAS has estimated the sensitivity at HL-LHC mainly by scaling the cross sections of the Run I analysis [13] to $\sqrt{s} = 14$ TeV. CMS has performed a study using DELPHES [14], requiring exactly four identified and isolated leptons (muons or electrons). The leading (subleading) lepton must have $p_T > 20$ (10) GeV or the leading lepton must have more than 30 GeV transverse momentum, the other two leptons must have p_T above 10 GeV (5 GeV for muons). The leptons must be consistent with the production of two Z bosons.

The expected sensitivity for the gluon fusion process is shown in Figure 3.

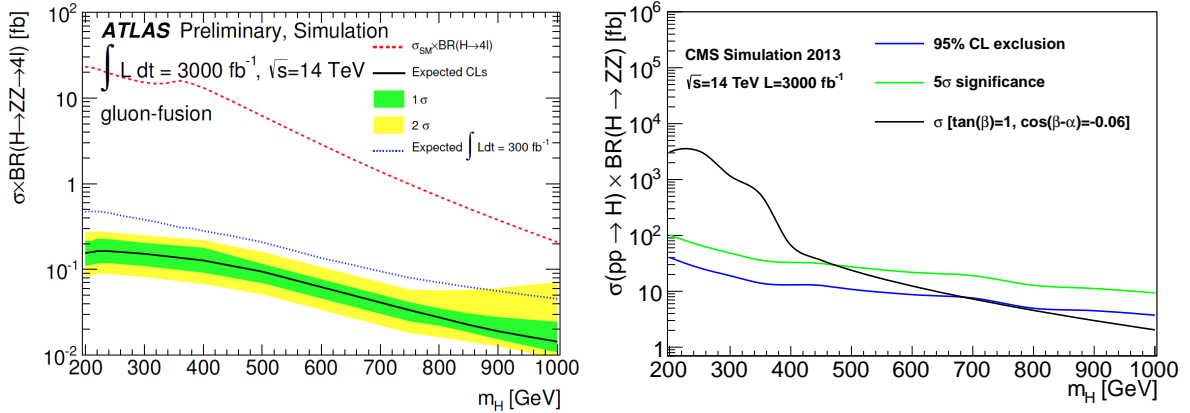


FIG. 3. Exclusion sensitivity as function of the heavy CP-even Higgs mass m_H for the gluon fusion production mechanism, for the ATLAS study [11] (left) and the CMS study [12] (right; branching ratio $ZZ \rightarrow 4\ell$ not included).

B. $pp \rightarrow A \rightarrow Zh \rightarrow \ell^+ \ell^- b \bar{b}$

The selections in the search for the pseudoscalar Higgs boson A are very similar for both experiments: two leptons (electrons or muons) are required (where the CMS study has separate p_T thresholds for the leading and subleading lepton) which must be consistent with a Z boson decay. Two b-jets must be present and must form an invariant mass in a relatively large window around the standard model Higgs mass. Both experiments use a b-tag selection corresponding to a b-jet signal efficiency of 70%.

In order to further discriminate against backgrounds, the ATLAS study requires $\Delta R(bb)$ to be within a (slightly m_A dependent) range, while CMS imposes an upper bound on $\Delta\phi(\ell\ell)$, a lower bound on the transverse momentum of the dilepton system and requires the ratio of the transverse momenta $p_T(Z)/p_T(h)$ to be within a certain range covering one.

To improve the mass resolution for the A boson with respect to the straightforward four body mass, ATLAS uses the following variable:

$$m_A^{\text{rec}} := m_{\ell\ell bb} - m_{\ell\ell} - m_{bb} + m_Z + m_h$$

i.e. the reconstructed dilepton and dijet masses are replaced by the nominal Z and Higgs masses m_Z and m_h .

Expected sensitivities for this channel at HL-LHC are shown in Figure 4.

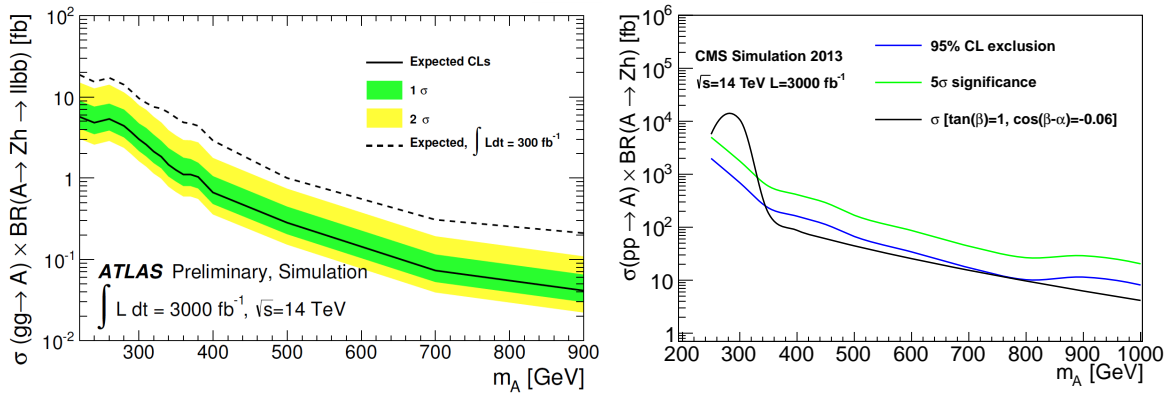


FIG. 4. Exclusion sensitivity as function of the CP-odd Higgs mass m_A , for the ATLAS study [11] (left) and the CMS study [12] (right; branching ratio $hZ \rightarrow b\bar{b}\ell\ell$ not included).

C. $pp \rightarrow H/A \rightarrow \mu^+\mu^-$

At high values of $\tan\beta$, the decays of A and H to $\mu^+\mu^-$ becomes relevant and is complementary to the $A \rightarrow hZ$ channel. Furthermore, this channel benefits from an excellent mass resolution. In the ATLAS study, exactly two muons with opposite charge are required. Events are split into two categories to better exploit the features of the two dominant production mechanisms gluon fusion (no b-tagged jet allowed) and b-associated production (at least one b-tagged jet required).

The 5σ reach for both categories combined is shown in Figure 5.

IV. TOP QUARK DECAYS INVOLVING FLAVOUR CHANGING NEUTRAL CURRENTS

In the standard model, where flavour changing neutral currents are not present at tree level, top decays to a charm quark and a Higgs boson are expected to have a branching ratio of $10^{-15} - 10^{-13}$ [15, 16] which is below the experimental sensitivity. However, several extensions of the standard model predict a branching ratio enhanced by several orders of magnitude, including type III two Higgs doublet models (in which tch couplings exist at tree level) where this branching ratio can be as high as $\approx 10^{-3}$ [15].

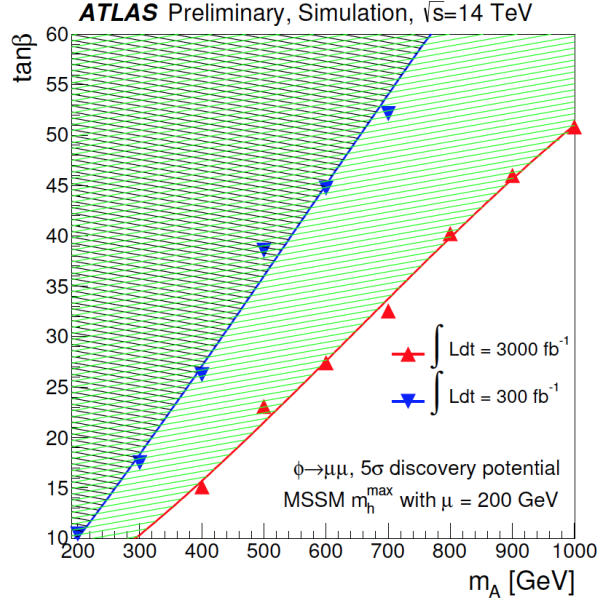


FIG. 5. Expected 5σ reach in the m_A vs. $\tan\beta$ plane for the m_h^{\max} MSSM benchmark scenario for the ATLAS [11] $A/H \rightarrow \mu^+\mu^-$ analysis.

ATLAS [17] has estimated the sensitivity at HL-LHC to decays $t \rightarrow ch$ based on the Run I analysis [18]. The selection focuses on the (very clean) decays of Higgs bosons to a pair of photons (despite the small branching ratio).

First two photons with transverse energy greater than 40 (30) GeV for the leading (subleading) photon are required. The next steps reflect the possible decay modes of the W boson in the other top decay:

- **hadronic W decays:** no charged lepton must be identified in the event and at least four jets with $p_T > 25$ (30) GeV in the central (non-central) region must be present.
- **leptonic W decays:** exactly one charged lepton is required which must have a transverse momentum above 20 GeV. At least two jets above 25 (30) GeV transverse momentum in the central (non-central) region must be present. The transverse mass, formed by the missing transverse energy and the lepton must be larger than 30 GeV. The longitudinal component of the neutrino momentum is estimated from the missing transverse energy and the charged lepton momentum imposing a W mass constraint.

In both channels, at least one jet must be identified as a b-jet. To ensure consistency with the production of a pair of top quarks, both top decays must have reconstructed top masses close to the nominal top mass for one assignment of jets to the two top decays.

The expected limit on the branching ratio $t \rightarrow ch$ after 3000 fb^{-1} , obtained from counting the number of events for which $123 \leq m_{\gamma\gamma} \leq 129 \text{ GeV}$, is $1.5 \cdot 10^{-4}$ at 95% CL. For comparison, the strictest observed limit after LHC Run I is 0.56% [19].

V. CONCLUSIONS AND OUTLOOK

We summarised ATLAS and CMS studies of the sensitivity to beyond the standard model Higgs physics after 3000 fb^{-1} in three areas: anomalous quartic couplings in vector boson scattering,

generic two Higgs doublet models and flavour changing top decays via Higgs bosons. To make the estimates more realistic, these studies will have to be updated using a detailed simulation of the upgraded detectors with complete simulated events and make use of reconstruction algorithms which have been re-optimised to deal with the increased pileup at HL-LHC.

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